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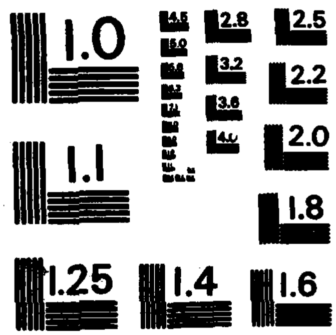

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VLSI ARRAY PROCESSOR FOR SIGNAL PROCESSING

UNIVERSITY OF SOUTHERN CALIFORNIA

FINAL REPORT

CONTRACT NO.: N00014 - 80 - C - 0457

Sponsored by

OFFICE OF NAVAL RESEARCH

Covering Research Activity During the Period
1 April 1980 through 31 March 1982

Sun-Yuan Kung
Principal Investigator
Department of Electrical Engineering - Systems
Los Angeles, California 90089 - 0272

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This report describes the research activities performed by the University of Southern California for the period 1 April 1980 to 31 March 1982 under the Contract No. N00014 - 80 - C - 0457 with the Office of Naval Research. The research activities have focussed on the VLSI array processor for signal processing theory and algorithms and the development of parallel computing architectures.

A solution in today's VLSI research challenge lies in a cross-disciplinary research encompassing the areas of mathematics, algorithms, computers, and ap-

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ABSTRACT

This report describes the research activities performed by the University of Southern California for the period 1 April 1980 to 31 March 1982 under the Contract No.: N00014 - 80 - C - 0457 with the Office of Naval Research. The research activities have focussed on the VLSI array processor for signal processing theory and algorithms and the development of parallel computing architectures.

A solution in today's VLSI research challenge lies in a cross-disciplinary research encompassing the areas of mathematics, algorithms, computers, and applications. To this end, this report summarizes two parallel major research tasks: (1) Signal processing algorithm and theory and (2) parallel computing structures.

INTRODUCTION

With the rapidly growing microelectronics technology leading the way, modern signal processing is undergoing a major revolution. The availability of low cost, fast VLSI devices promises the practice of increasingly complex and sophisticated algorithms and systems. However, in conjunction with such promise, there is accompanied a new challenge of how to update the signal processing techniques so as to effectively utilize the large-scale computation capability. The answer to this challenge lies in a cross-disciplinary research encompassing the areas of mathematics, algorithms, computers and applications. To this end, two parallel major research tasks have been undertaken in the ONR research group:

(1) Signal processing algorithm and theory - emphasizing spectral analysis and its applications;

(2) Parallel computing structures - utilizing VLSI potential for high-speed signal processing.

In the area of signal processing theory and algorithms, significant work has been made on the following topics with special emphasis on high resolution spectral estimation: adaptive notch filtering; MEM, ARMA, and ML spectral estimation in 1-D and 2-D; and Toeplitz approximation. Parallel implementation of these algorithms has been a major consideration in their development.

In the complimentary area of parallel computing structures, both dedicated and flexible architectures have been developed for signal processing tasks and applications. Works in progress include: Toeplitz system solver using pipelined Levinson and implementation and programmable

wavefront array processor and data flow language for VLSI signal processing algorithms, systolic arrays for real-time signal processing applications in spectrum analysis and direction finding and systolic architectures for ladder forms and parallel Kalman filters.

A brief summary of the technical work, grouped in terms of research is described in the following sections.

Signal Processing Algorithm and Theory

As to the first research front, it hinges upon a thorough, in-depth understanding of mathematics and algorithm analysis. In addition to the classical mathematical techniques such as Fourier transform, linear dynamic systems, random process, etc., there arises a new signal processing mathematics branch which can be grossly termed as modern spectral analysis. Explicitly or not, a large class of signal processing applications have had extensive use of this analysis as a technical basis. Therefore, our research effort aims at developing a theoretical and algorithmic basis for modern spectral analysis methods and signal processing applications.

Adaptive Notch Filtering

Using a steady state frequency domain approach, a new method has been developed for the retrieval of sinusoids/narrowband signals in additive noise colored or white. The method suggested has been shown to require smaller filter length to produce unbiased estimates, compared to the existing autoregressive method. For its implementation, a pole-zero filter where the feedback and feedforward coefficients are related (constrained ARMA), has been developed. A study of the performance and implementational

aspects of the filter have been undertaken. The details of this newly developed are discussed in the full report. For a stable implementation, parallel and cascade forms have been shown to be useful. A parallel processing scheme developed shows great promise.

Spectral Estimation

Our recent research has been concerned with developing systematic methods for 2-D spectral estimation from raw data using random field models. We assume that the given finite data is represented by an appropriate Gaussian Markov random field (MRF) model.

By using specific finite toroidal lattice representations and Gaussian maximum likelihood estimates we have developed new 2-D spectral estimates. It turns out that the MRF spectrum is also the maximum likelihood spectrum arising in frequency-wave number analysis. Furthermore, the sample correlation values of the given observations in an array N are in perfect agreement with the estiamted theoretical correlations in N obtained by Fourier inverting the MRF spectrum. Thus the MRF spectrum developed by us converges to the 2-D maximum entropy spectral estimate asymptotically. Currently we have begun investigations on parallel implementation of the algorithms for 2-D spectral estimation.

Relationship Between Several Popular Methods for Spectral Estimation and Array Processing

It may seem too ambitious to compare all currently popular high-resolution spectral estimation methods. For example, while maximum entropy method related to autoregressive modeling is receiving a tremendous popularity, it may suffer from bias and resolution problems when additive noise is non-negligible. On the other hand, Pisarenko's method based on sinusoidal modeling enjoys relatively better performance in the presence of noise but in general suffers from numerical sensitivity problems. However, from a difference perspective, Pisarenko's method can be viewed as an extension of the MEM method with the removal of the noise contribution. Therefore, an attempt is being made at developing a unified framework for the spectral analysis techniques. Moreover, the unification attempt is being extended to the counterpart of spectral analysis in array processing application. Though the covariance matrix will no longer have a Toeplitz structure and the phasing vectors are more complex in array processing situations, we are convinced that the general principles remain largely applicable. We are currently looking into theoretical and computational relevances between several modern array processing and spectrum estimation methods.

Toeplitz Approximation Method

Recently, the study on approximation teory and its applications has received considerable attention. In our work, a narrowband/sinusoidal signal retrieval problem is formulated in terms of approximation of Toeplitz autocovariance matrix. A Toeplitz approximation method based on singular value decomposition is proposed and simulation results indicate

some improvement over some previously proposed methods.

Parallel Algorithms for Image Processing and Analysis

Our recent research at Image Processing Institute at USC has been concerned with parallel algorithms for image processing and image analysis. Most of the effort has been concerned with parallel implementation of nonstationary adaptive image restoration. Recursive and non-recursive implementation of locally adaptive restoration has been studied. These techniques estimate the local nonstationary mean and variance of ideal scenes from degraded data. Most blurring degradations are also highly local, so that local parallel processing combined with the nonstationary image model data can be used to minimize local mean-square error (MSE) in a parallel fashion. We have shown that local MSE is not a bad error criterion for image processing, as opposed to the usual global MSF taken over the entire scene. Global MSE often does not correlate well with human observer judgments of image quality.

We have looked at the application of these techniques to systems with coherent speckle noise, such as synthetic aperture (SAR) imagery, coherent sonar and acoustic imaging. Both recursive (Kalman-like) and local sectioned parallel implementations are being studied in detail.

In addition, we have began investigations on parallel feature extraction for texture identification and texture segmentation.

A Parallel Algorithm for Solving Toeplitz System

We have developed a parallel algorithm for solving a Toeplitz system

$Tx = y$ where T is a Toeplitz matrix, i.e., $[T]_{ij} = t_{i-j} = t_k$, $-N \leq k \leq N$. In general, solving an N by N linear systems takes O(N**3) steps of operations. In contrast, the Levinson algorithm effectively utilizes the Toeplitz structure to reduce the overall computation to O(N**2) operations. The Levinson procedure, however, has to call upon an inner product operation to compute the vital reflection coefficients. In order to achieve full parallelism, we have to further exploit the Toeplitz structure. For this purpose, we have proposed a new, pipelined version of the Levinson algorithm which allows the reflection coefficients to be computed in a pipelined fashion. This avoids the need of the inner product operations, and the total computing time is therefore reduced to O(N).

<u>Toeplitz Eigenvalue Computation</u>

This research task deals with the parallel computation of the minimum eigenvalue of a Toeplitz matrix. The minimum eigenvalue has an important interpretation as the power of additive, white noise to be determined in noisy statistical environment. In many high resolution spectrum analysis problems, the estimation and removal of such noise contribution is essential for unbiased estimates. Our objective is again to derive an O(N) Computation algorithm to estimate the minimum eigenvalue of a given Toeplitz covariance matrix. This goal can be accompanied by adopting the pipelined Toeplitz computing structure discussed earlier and a careful utilization of a relationship between the minimum eigenvalue and the radiuses E that arise in the Levinson algorithm. Based on this relationship, a fast iterative procedure is developed to successively

estimate the minimum eigenvalue. Based on simulation results for such an application, some improvements are observed in both the computing speed as well as accuracy of estimates. Although much more computational complexity analysis is yet to be demonstrated, we are convinced that this approach will have a major in future applications of high speed, high resolution spectrum estimation problems.

Application of SVD to Signal Processing

It is well known that SVD can be used in many signal processing applications. Therefore parallel (real-time) implementation has been an important research focus. Some partial results are offered in the report. The most noteworthy result is the significant numerical improvement of 60bd in terms of dynamic range obtained in the computation of eigenvalue of $R = A \ A$ via SVD of A. This approach is being extended to generalized eigensystem computation.

Parallel Algorithms for Seismic Signal Processing

Parallel Processing techniques for generating synthetic seismograms and for the computation of the output of a horizontally stratified, non-absorptive medium propagating plane waves vertically; have been studied.

Highly Parallel Computing Structures

The aforementioned research effort on signal processing algorithm and theory, equipped with parallel algorithms, and adaptive on-line processing techniques, will serve as a useful cornerstone for real-time high

performance signal processing area. However, the real major thrust for high-speed signal processing lies in effective utilization of the enormous computation capability provided by the VLSI circuits. Therefore, our research task aims to bring the revolutionary VLSI device technology to an effective signal processing application.

Pipelined Toeplitz System Solver [ ]

This new parallel algoritnm for solving Toeplitz system can be implemented for parallel computation with full compliance with the VLSI communication constraint. Specifically, a pipelined processor architecture with O(N) processors is developed which uses only localized interconnections and still retains the maximum parallelism attainable.

We believe that the proposed pipelined Toeplitz system solver [ ] is perhaps the most efficient, fast, and practical (in VLSI sense) design available for solving Toeplitz systems. Moreover, the design methodology demonstrated in this work should also help answer some fundamental problems faced in designing of VLSI parallel processor architectures.

Wavefront Array Processor

The traditional design of parallel computers and languages is not very suitable for the design of VLSI array processors for signal processing. VLSI imposes the restrictions of local data-dependence and recursivity on the algorithms that can be handled by such an array processor. Such algorithms can be viewed as a sequence of waves (of data and computational activity). This naturally leads to a wavefront based programmable computing network, which we call the Wavefront Array Processor (WAP).

Our contribution hinges upon the development of a wavefront-based language and architecture for a programmable special purpose multiprocessor array. Based on the notion of computational wavefront, the hardware of the processor array is designed to provide a computing medium that preserves the key properties of the wavefront. In conjunction, a wavefront language (MDFL) is introduced that drastically reduces the complexity of the description of parallel algorithms and simulates the wavefront propagation across the computing network. Together, the hardware and the language lead to a programmable Wavefront Array Processor (WAP). The WAP blends the advantages of the dedicated systolic array and the general purpose Data-Flow machine and provides a powerful tool for the high speed execution of a large class of matrix operations and related algorithms which have widespread applications.

Summary and List of Publications

1 PARALLEL COMPUTING STRUCTURES (S.Y.Kung, Y.H.Hu, R.Gal-ezer, K.S.Arun ,D.V.B.Rao)

With the rapidly growing microelectronics technology leading the way, modern signal processor architectures are undergoing a major revolution. The availability of low cost, fast VLSI (Very Large Scale Integration) devices promises the practice of cost-effective, high speed, parallel processing of large volume of data. This makes possible ultra high throughput-rate and therefore, designates a major technological breakthrough for real-time signal processing applications. On the other hand, it has become more critical than ever to gain a fundamental understanding of the algorithm structure, architecture, and implementation constraints in order to realize the full potential of VLSI computing power. In our work, the two most critical issues - parallel computing algorithm and VLSI architectural constraint will be considered:

1. To structure the algorithm to achieve the maximum parallelism and, therefore, the maximum throughput-rate.
2. To cope with the communication constraint so as to compromise least in processing throughput-rate.

1.1 A highly concurrent Toeplitz system solver [5-6]

Based on the above considerations, we have developed a highly concurrent Toeplitz system solver, featuring maximum parallelism and localized communication.

Toeplitz systems arise in numerous, wide-spread applications ranging from speech, image, neurophysics, to radar, sonar, geophysics, and astronomical signal processing . Our contribution lies in the

development of a highly concurrent algorithm and pipelined architecture which is able to solve a Toeplitz system in O(N) processing time in an array proecssor, as opposed to O(N**3) for general (sequential) Gauss elimination procedure or O(N**2) for (sequential) Levinson algorithm.

For parallel consideration, we note that the Levinson procedure has to call upon an inner product operation to compute the vital "reflection coeffecients". Even when N processors is utilized, an inner product operation will need at least logN units of time. This will amount to a total of O(NlogN) units of computing time for the entire Levinson procedure. This is of course unsatisfactory since the processors are not effectively utilized.

In order to achieve full parallelism, we have to further exploit the Toeplitz structure. For this purpose, we have proposed a new, pipelined version of the Levinson algorithm which allows the reflection coefficients to be computed in a pipelined fashion. This avoids the need of the inner product operations, and the total computing time is therefore reduced to O(N).

This new algorithm can be implemented in full compliance with the VLSI communication constraint. More precisely, a pipelined processor architecture is developed which uses only localized interconnections and still retains the maximum parallelism attainable.

In summary, we believe that the proposed pipelined Toeplits system solver is perhaps the most efficient, fast, and practical (in VLSI sense) design available for solving Toeplitz systems. Moreover, the

design methodology demonstrated in this work should also help answer some fundamental problems faced in designing of VLSI parallel processor architectures.

1.2 Toeplitz Eigenvalue Computation [36]

This research task deals with the parallel computation of the minimum eigenvalue of a Toeplitz matrix. The minimum eigenvalue has an important interpretation as the power of additive, white noise to be determined in a noisy statistical environment. In many high resolution spectrum analysis problems, the estimation and removal of such noise contribution is essential for unbiased estimates. Our objective is again to derive an $O(N)$ computation algorithm to estimate the minimum eigenvalue of a given Toeplitz covariance matrix. This goal can be accomplished by adopting the pipelined Toeplitz computing structure discussed earlier and a careful utilization of a relationship between the minimum eigenvalue and the redisues E that arise in the Levinson algorithm. Based on this relationship, a fast iterative procedure is developed to successively estimate the minimum eigenvalue. Based on simulation results for such an application, some improvements are observed in both the computing speed as well as accuracy of estimates. Although much more computational complexity analysis is yet to be demonstrated, we are convinced that this approach will have a major in future applications of high speed, high resolution spectrum estimation problems.

1.3 Wavefront Array Processor

The traditional design of parallel computers and languages usually suffers from heavy supervisory overhead incurred by synchronization, communication, and scheduling tasks, which severely hamper the throughput rate which is critical to real-time signal processing.

Furthermore, additional restrictions imposed by VLSI will render the general purpose array processor very inefficient. We therefore restrict ourselves to a special class of applications, i.e. recursive and local data dependent algorithms, to conform with the constraints imposed by VLSI. however, this restriction incurs little loss of generality, as a great majority of signal processing algorithms possess these properties. One typical example is a class of matrix algorithms.

Very significantly, these algorithms involve repeated application of relatively simple operations with regular localized data flow in a homogeneous computing network. This leads to an important notion of computational wavefront, which portrays the computation activities in a manner resembling a wave propagation phenomenon. More precisely, the recursive nature of the algorithm, in conjunction with the localized data dependency, points to a continuously advancing wave of data and computational activity.

The wavefront concept, provides a firm theoretical foundation for the design of highly parallel array processors and concurrent languages. Moreover, this concept appears to have some distinct advantages.

Firstly, the wavefront notion drastically reduces the complexity in

the description of parallel algorithms. The mechanism provided for this description is a special purpose, wavefront-oriented language. Rather than requiring a program for each processor in the array, this language allows the programmer to address an entire front of processors.

Secondly, the wavefront notion leads to a wavefront- based architecture that conforms with the constraints of VLSI, and supports a major class of signal processing algorithms. As a consequence of Huygen's principle, wavefronts should never intersect. With a wavefront architecture that provides asynchronous waiting capability, this principle is preserved. Therefore, the wavefront approach can cope with timing uncertainties, such as local clocking, random delay in communications and fluctuations of computing-times. In short, there is no need for global synchronization.

Thirdly, the wavefront notion is applicable to all VLSI signal processing algorithms that possess locality and recursivity, and hence, has numerous applications.

The integration of the wavefront concept, the wavefront language and the wavefront architecture leads to a programmable computing network, which we will call the WAVEFRONT ARRAY PROCESSOR (WAP).The WAP is,in a sense,an optimal tradeoff between the globally synchronized and dedicated systolic array (that works on a similar set of algorithms), and the general-purpose data-flow multiprocessors. It provides a powerful tool for the high speed execution of a large class of algorithms which have widespread applications. The applications are very broad including PDE solver, SVD, linear systems solvers, sorting

and searching routines.

There exist two approaches approaches to programming the WAP: a local approach, describing the actions of each processing element, and a global approach, describing the actions of each wavefront. To allow the user to program the WAP in both these fashions, two versions of MDFL are proposed: global and local MDFL. A global MDFL program describes the algorithm from the view-point of a wavefront, while a local MDFL program describes the operations of an individual processor. More precisely, the perspective of a global MDFL programmer is of one wavefront passing across all the processors, while the perspective of a local MDFL programmer is that of one processor encountering a series of wavefronts.

In summary, our contribution hinges upon the development of a wavefront-based language and architecture for a programmable special purpose multiprocessor array. Based on the notion of computational wavefront, the hardware of the processor array is designed to provide a computing medium that preserves the key properties of the wavefront. In conjunction, a wavefront language (MDFL) is introduced that drastically reduces the complexity of the description of parallel algorithms and simulates the wavefront propagation across the computing netwrok. Together, the hardware and the language lead to a programmable Wavefront Array Processor (WAP). The WAP blends the advantages of the dedicated Systolic array and the general purpose Data-Flow machine and provides a powerful tool for the high speed execution of a large class of matrix operations and related algorithms which have widespread applications.

2 SIGNAL PROCESSING ALGORITHMS AND THEORY (S.Y.Kung, Y.H.Hu, D.V.B.Rao)

As to this research front, it hinges upon a thorough, in-depth understanding of mathematics and algorithm analysis. In addition to the classical mathematical techniques such as Fourier transform, linear dynamic systems, random process, etc. there arises a new signal processing mathematics branch which can be grossly termed as modern spectral analysis. Explicitly or not, a large class of signal processing applications have had extensive use of this analysis as a technical basis. Therefore, our research effort aims at developing a theoretical and algorithmic basis for modern spectral analysis methods and signal processing applications.

2-1 Adaptive Notch Filtering (USC [1-3])

Using a steady state frequency domain approach, a new method has been developed for the retrieval of sinusoids/narrowband signals in additive noise colored or white. The method suggested has been shown to require smaller filter length to produce unbiased estimates, compared to the existing autoregressive method. For its implementation, a pole-zero filter where the feedback and feedforward coefficients are related (constrained ARMA), has been developed. A study of the performance and implementational aspects of the filter have been undertaken. The details of this newly developed are discussed in the full report. For a stable implementation, parallel and cascade forms have been shown to be useful. A parallel processing scheme developed shows great promise.

2.2 Relationships Between Several Popular Methods for Spectral Estimation and Array Processing

It may seem too ambitious to compare all currently popular high-resolution spectral estimation methods. However, from a different perspective, Pisarenko's method can be viewed as an extension of the MEM method with the removal of the noise contribution. Therefore, an attempt is being made at developing a unified framework for the spectral analysis techniques. Moreover, the unification attempt is being extended to the counterpart of spectral analysis in array processing application, for which we are convinced that the general principles remain largely applicable. We are currently looking into theoretical and computational relevances between several recent array processing and spectrum estimation methods.

2.3 Toeplitz Approximation Method (USC[4])

Recently, the study on approximation theory and its applications has received considerable attention. In our work, a narrowband/sinusoidal signal retrieval problem is formulated in terms of approximation of Toeplitz autocovariance matrix. A Toeplitz approximation method based on singular value decomposition is proposed and simulation results indicate some improvement over some previously proposed methods.

3 REVIEW OF RESEARCH ACTIVITIES IN IPI, USC (A.A.Sawchuk, R.Chellappa)

3.1 Parallel Algorithms for Image Processing and Analysis

Our recent research at Image Processing Institute,USC, has been concerned with parallel algorithms for image processing and image analysis. Most of the effort has been concerned with parallel implementation of nonstationary adaptive image restoration. Recursive and non-recursive implementation of locally adaptive restoration has been studied. These techniques estimate the local nonstationary mean and variance of ideal scenes from degraded data. Most blurring degradations are also highly local, so that local parallel processing combined with the nonstationary image model data can be used to minimize local mean-square erro (MSE) in a parallel fashion. We have shown that local MSE is not a bad error criterion for image processing, as opposed to the usual global MSE taken over the entire scene. Global MSE often does not correlate well with human observer judgments of image quality.

We have looked at the application of these techniques to systems with coherent speckle noise, such as synthetic aperature (SAR) imagery, coherent sonar and acoustic imaging. Both recursive (Kalman-like) and local sectioned parallel implementations are being studied in detail. In addition, we have began investigations on parallel feature extraction for texture identification and texture segmentation.

3.2 Two Dimensional Spectral Estimation

Two-dimensional spectral estimation is of interest in image restoration, filtering of SAR images and texture classification. Our recent research has been concerned with developing systematic methods for 2-D spectral estimation from raw data using random field models. We assume that the given finite data is represented by an appropriate

Gaussian Markov random field (MRF) model.

This assumption reduces the spectral estimation problem to that of estimating the appropriate structure and the parameters of the model. By using specific finite toroidal lattice representations and Gaussian maximum likelihood estimates we have developed new 2-D spectral estimates. It turns out that the MRF spectrum is also the maximum likelihood spectrum arising in frequency-wave number analysis. Furthermore, the sample correlation values of the given observations in an array N are in perfect agreement with the estimated theoretical correlations in N obtained by Fourier inverting the MRF spectrum. Thus the MRF spectrum developed by us converges to the 2-D maximum entropy spectral estimate asymptotically. Currently we have begun investigations on parallel implementation of the algorithms for 2-D spectral estimation.

In addition, we are also investigating the use of another class of random field models known as spatial autoregressive models which are white noise driven non causal models for spectral estimation.

4 PARALLEL PROCESSING TECHNIQUES FOR SEISMIC PROCESSING (J.Mendel, J.Goutsias)

Because of the large volume of information involved in the simulation and processing of seismic data, and the amount of processing required, parallel techniques have begun to be studied. The recent development of VLSI systems and the growing sophestication in the design of array processors xan lead to the effecient simulation of large seismic models. We are examining some possible parallel processing techniques for the

computation of the output of a horizontally stratified, non absorbtive medium in which there are vertically travelling plane compressional waves.

This task has just been started and we intend to look at different parallel structures for generating synthetic seismograms.

Selected publications under Contract number ONR N00014-81-K-0191 :

University Of Southern California

1. S.Y.KUNG and D.V.Bhaskar Rao, " An Unbiased Adaptive Method For Retrieval Of Sinusoidal Signals in Colored Noise", Proc. IEEE 20th CDC, San Diego, CA, Dec 1981

2. S.Y.Kung and D.V.Bhaskar Rao, " New Unbiased Methods For Narrowband Spectral Estimation", IFAC, NEW DELHI, India, 1982

3. S.Y.Kung and D.V.Bhaskar Rao, " Analysis and Implementation Of The Adaptive Notch Filter For Frequency Estimation", Proc. ICASSP, PARIS, MAY 3-5, 1982.

4. S.Y.Kung, " A Toeplitz Approximation Method and Some Applications", Int. Symp. on Math. Soc. of networks and Systems, Santa Monica, CA, Aug. 5-7, 1981

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6. S.Y.Kung and Yu-Hen Hu, " Fast and Parallel Algorithms For Solving Toeplitz Systems", Proc. ISMM, San Francisco, May 1981.

7. S.Y.Kung and Yu-Hen Hu, " A Highly Concurrent Algorithm and Pipelined Architecture For Solving Toeplitz Systems", Submitted to ASSP, 1982.

8. S.Y.Kung, " Matrix Data Flow Language for Matrix-Operation-Dedicated Array Processors", Proc. Europe Conf. Circuit Theory and Design, Hague, Netherlands, Aug. 1981.

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10. S.Y.Kung et.al.," A Matrix Data Flow Language/Architecture For Parallel Matrix Operations Based On Computational Wavefront Concept", Proc. CMU Conf. On VLSI Syst. and Computations, Oct. 1981.

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13. R.Chellappa and S.Y.Kung, "On Two Dimensional Markov Spectral Estimation", CISS, Princeton, Mar. 1982

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14. H.J.Whitehouse and J.M.Spieser, " Sonar Applications Of Systolic Array Technology", Conf. IEEE Eascon,Nov. 1981.